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THE SUBDUCTION FACTORY OF THE AEOLIAN VOLCANIC ARC

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Abstract

The Aeolian volcanic arc, emplaced on continental lithosphere, is composed of seven islands and seven seamounts. The islands are formed by lava flows, domes and pyroclastic deposits, and emerged from the sea in a short span of time, from ~200 ka ago at Filicudi, Lipari and Stromboli (Strombolicchio neck), to ~100 ka at Alicudi and Stromboli. The oldest rocks with 1.3 Ma are from Sisifo seamount; at Panarea, an intense fumarolic activity is still present, and the last eruptions at Lipari took place in 580 AD, whereas Vulcano and Stromboli are still active. The rock compositions belong to different magmatic series of continental active margins, and exhibit a large silica range (48-76 wt%). Calc-alkaline and high-K calc-alkaline magmas are present in all the islands. Shoshonitic rocks are found at Lipari, Vulcano, Panarea, and Stromboli. Potassic magmas have been erupted only at Vulcano and Stromboli.

Significant compositional variations of erupted magmas are observed both between and within each volcano. Basalts are not found at Lipari, whereas a large amount of rhyolites, having different petrochemical characteristics, are present in the central arc islands (Lipari, Vulcano, Salina, Panarea). Aeolian volcanic arc magmas underwent multiple differentiation processes *en route* to the surface. Fractional crystallization has been often associated to crustal contamination which affected both the most evolved magmas at Vulcano, Salina and Lipari and the most mafic magmas at Alicudi, Filicudi and Stromboli. Multiple magma mixing also played an important role and has been often associated to the other differentiation processes. These evolutionary processes were polybaric and occurred at different depths in the different volcanoes; the highest crystallization pressure has been determined for Filicudi and Salina magmas.

The trace element characteristics of the less evolved magmas of the Aeolian volcanic arc vary from the central to the external parts of the archipelago, whereas isotope ratios mostly change from the western to the eastern sector of the arc. Overall the complete set of data demonstrates that the genesis of the different parental magmas of the Aeolian volcanic arc can be accommodated in a MORB-like mantle wedge source that experienced enrichment processes by subduction-related components of the oceanic crust (basalt + sediment) of the Ionian slab released predominantly as melts and subordinately as aqueous fluids. The latter have a more significant role in the calc-alkaline rocks of the central sector of the arc.

The geochemical and radiogenic isotope signature of the mantle wedge beneath the Aeolian volcanic arc places important constraints on the isotopic polarity from Southern Latium to the Aeolian arc attributed to the effect of a HIMU mantle component following either lateral inflow of foreland mantle material or upwelling of a mantle plume in the centre of the Tyrrhenian basin. The high $^{206}Pb/^{204}Pb$ of the putative 'HIMU' mantle component could have equally been formed during metasomatism of the pre-existing mantle wedge by melts released from the subducted altered basalt of the Ionian slab.

Keywords: Aeolian Volcanic Arc, Trace Elements, Radiogenic Isotopes, Mantle Metasomatism

1. Introduction

A general review of the main geochemical and isotopic characteristics of the Aeolian volcanic arc is reported in this paper and is dedicated to the memory of Fabrizio Innocenti a leading scientist of the Italian Earth Sciences community. Although he did not devoted his research activity to the Aeolian volcanic arc but one manuscript in the early 70s (Bàrberi *et alii* 1973), his contribution to the understanding of Italian magmatism and subduction-related magmatism has been fundamental and will remain as a milestone for the future generations of Earth Scientists.

The Aeolian arc is located on the south-eastern continental slope of the Tyrrhenian abyssal plain, on a 15-20 km-thick continental crust (Morelli *et alii* 1975). It consists of seven main volcanic Islands (Alicudi, Filicudi, Salina, Lipari, Vulcano, Panarea, Stromboli) and seven Seamounts (Lametini, Alcione, Palinuro, Marsili, Sisifo, Enarete, Eolo), which form an approximate ring-like structure (Fig. 1). Palinuro represents a volcanic complex, the easternmost Volcano of which, Glabro, has an outstanding morphology and an unknown composition (Marani and Gamberi 2004). The age of the volcanism ranges from 1.3 Ma (basalt from Sisifo Seamount) to present time (Beccaluva *et alii* 1985, Santo *et alii* 1995, De Rosa *et alii* 2003). Historic eruptions have been recorded at Lipari, and submarine fumarolic activity has been registered very close to Panarea (2002-2003 AD), whereas Vulcano and Stromboli Volcanoes are still active. The islands are mainly formed by composite volcanoes consisting of lava flows, domes, and pyroclastic deposits. The Aeolian Volcanoes are related to the still-active subduction of the Ionian plate beneath the Calabrian arc (Fig. 1). A steep (60°-70°) NW-dipping Benioff zone has been recognized below the arc on the basis of the distribution of intermediate- and deep-earthquake hypocenters (Caputo *et alii* 1970, Bàrberi *et*

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FIG. 1. Schematic map showing the location of the Aeolian Islands Volcanoes (in black) and seamounts. TLM - Tindari-Letojanni-Malta escarpment transcurrent fault.

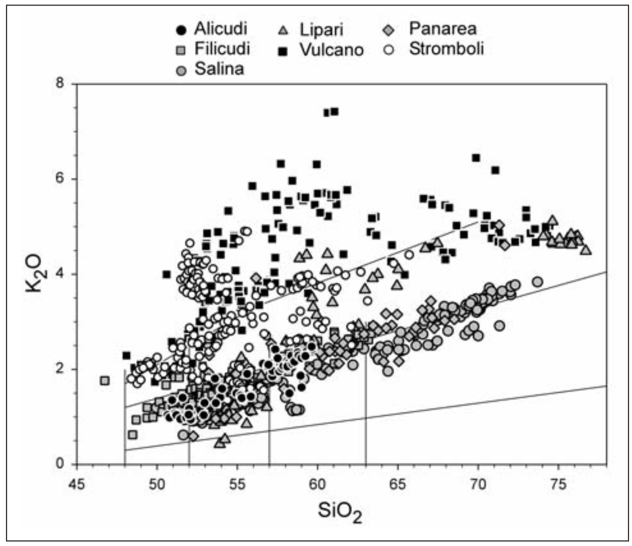

FIG. 2. K_2O *vs* SiO_2 classification diagram for the rocks of the Aeolian volcanic arc. Data source: Romano (1973), Keller (1980a, 1980b), Francalanci *et alii* (1988, 1989, 1993a, 1993b, 2007), Bargossi *et alii* (1989), Ellam *et alii* (1989), Crisci *et alii* (1991), Esperança *et alii* (1992), Peccerillo and Wu (1992), Calanchi *et alii* (1993, 2002), Francalanci and Santo (1993), Peccerillo *et alii* (1993), Ventura (1995), De Astis *et alii* (1997, 2000), Del Moro *et alii* (1998), Gertisser and Keller (2000), Gioncada *et alii* (2003), Santo *et alii* (2004), Tommasini *et alii* (2007).

alii 1973, Scandone 1982, Boccaletti *et alii* 1984, Beccaluva *et alii* 1985, Patacca *et alii* 1990, Mantovani *et alii* 1996). The active deep seismicity is limited to the eastern branch of the arc, whereas it is absent beneath the western islands, and the Tindari-Letojanni-Malta escarpment transcurrent fault divides the two different tectonic regimes (FIG. 1 - Falsaperla *et alii* 1999, Peccerillo and Panza 1999).

2. GEODYNAMIC SETTING

A schematic outline of the geodynamic evolution of the Mediterranean region is first summarized to highlight a number of key points that are critical to assess the mantle source characteristics of the Aeolian volcanic arc. The Mediterranean domain provides a present-day geodynamic analogue for the early stages of continent-continent collision. The present-day structure of the Italian region is a consequence of the convergence of the African and Eurasian plates (for recent reviews, see Gueguen *et alii* 1998; Faccenna *et alii* 2003, 2007; Mattei *et alii* 2004). During the Tertiary, Africa has been slowly converging with Eurasia at a rate of 1-2 cm/year; and the total convergence in the central Mediterranean region is estimated to have reached 400-500 km during the past 90 Myr (*e.g.*, Dewey *et alii* 1989). The oceanic plates have been subducted or obducted almost completely, except for the last remnants occurring in the Ionian basin and Southeastern Mediterranean (Cavazza and Wezel 2003, Finetti 2005, Stampfli 2005). This process, combined with the Neogene retreat of the trench (*e.g.*, Gueguen *et alii* 1998; Gvirtzman and Nur 1999, 2001; Wortel and Spakman 2000; Faccenna *et alii* 2003), has caused the progressive closure of the intervening Mesozoic oceanic basins of the Western Tethyan domain, with the formation of a complex arcuate orogenic belt (Apennine-Maghrebide belt) and extensional back-arc basins (Ligurian-Provençal and Tyrrhenian basins). The Ionian-Adriatic lithosphere has been continuously subducted toward the N-W underneath the Eurasian plate. The present-day remnants of the Ionian plate consist of Triassic-Jurassic oceanic crust underneath a thick pile of Mesozoic and Cenozoic sediments (Catalano *et alii* 2001, Finetti 2005, Stampfli 2005).

The Apennine orogeny and associated back-arc extension were accompanied by long-lived volcanic activity that continues today. The magmas produced represent one of the most impressive features of the geodynamic evolution of Italy, and are characterized by a considerable petrological, geochemical and isotopic diversity (*e.g.*, Conticelli and Peccerillo 1992, Conticelli *et alii* 2002, Peccerillo 2003, Avanzinelli *et alii* 2008).

The main present-day geodynamic feature of the Italian region is a well-defined Benioff Zone (roughly 200 km wide, dipping N-W at ~70°) down to about 500 km, which reveals the still active process, although now almost exhausted, of subduction of the Ionian oceanic plate below Calabria and the Tyrrhenian Sea (*e.g.*, Meletti *et alii* 2000; Wortel and Spakman 2000; Faccenna *et alii* 2001, 2007; Panza *et alii* 2003). Thermal and rheological modelling of the subducting Ionian slab indicates a very cold subduction zone (Carminati *et alii* 2005, Pasquale *et alii* 2005), perhaps one of the coldest on Earth, implying the occurrence of dehydration and melting reactions at greater depths than in many other volcanic arcs.

3. THE AEOLIAN VOLCANIC ARC

The Aeolian volcanic rocks belong to the typical magmatic series occurring in subduction-related settings, varying from island arc tholeiite (limited to seamounts; Beccaluva *et alii* 1985) to calc-alkaline, high-K calc-alkaline and shoshonitic magma series closely associated in space and time (Fig. 2). Shoshonitic magmas at Stromboli and Vulcano have a large range of K_2O contents at a given silica content, hence a potassic series (KS) is also defined to distinguish the different potassium enrichment ($K_2O > 3.5$ wt% at $SiO_2 < 56$ wt%). The other shoshonitic rocks form a series straddling the boundary between the high-K calcalkaline and shoshonitic fields (Fig. 2). Basaltic to rhyolitic lavas, dredged from the eastern and western seamounts, mostly belong to calc-alkaline and shoshonitic series, with compositional characteristics similar to the subaerial rocks of the Aeolian Islands. A pillow lava field of mafic potassic composition has been recently discovered at about 2,300 m b.s.l. and 9 km north from the shoreline of Stromboli Island (Di Roberto *et alii* 2008). Mainly calc-alkaline rocks have been dredged at the Marsili Volcano, sited in the central part of the Marsili backarc basin on a basaltic oceanic crust of 1.9-1.7 Ma (Trua *et alii* 2002 and references therein). Island-arc tholeiitic basalts have been only dredged from north Lametini and lowermost Aeolian slope. The oldest calc-alkaline magmatic activity has been dated at 1.3-0.9 Ma to the west (Sisifo seamount), whereas the oldest shoshonitic volcanism, found at Eolo and Enarete seamounts, has an age of 0.85-0.64 Ma. There is no unique time-dependent variation of magmatic series in the different sectors of the arc, although a general increase of K_2O with time is observed at Vulcano and Stromboli. Also, no correlation between potassium content and the depth of the subducted slab exists.

3.1. *Volcanological and petrological Characteristics of the Aeolian Islands*

Alicudi, with an area of ~6 km² and an elevation of 654 m above sea level (asl), is the westernmost island of the Aeolian archipelago (Fig. 1). The oldest outcropping rocks are basaltic lavas with an age of ~87 ka, whereas andesitic lava flows characterized the final volcanic activity at ~28 ka (Manetti *et alii* 1995). The entire compositional variation of the Alicudi rocks ranges from calc-alkaline basalts to basaltic andesites and high-K calc-alkaline andesites (Fig. 2). The mafic rocks display the most primitive petrological and geochemical characteristics of the Aeolian arc (Figs. 2, 3, 5). $^{87}Sr/^{86}Sr$ ranges between 0.70342 and 0.70410 and is negatively correlated with Nd isotopes (0.51289-0.51279). The $\delta^{18}O$ values, calculated from data obtained on olivine and clinopyroxene, are low and fairly constant (5.0-5.6‰). Pb isotopes (Fig. 4) have the following variation: $^{206}Pb/^{204}Pb$ = 19.20-19.67, $^{207}Pb/^{204}Pb$ = 15.62-15.68, and $^{208}Pb/^{204}Pb$ = 39.07-39.36 (Peccerillo and Wu 1992; Francalanci *et alii* 1993b; Peccerillo *et alii* 1993, 2004).

Filicudi, with an elevation of 750 m a.s.l. and an area of ~9.5 km², represents the emergent part of a complex structure, which is elongated NW-SE and is parallel to the main regional lineaments (Fig. 1) (Calanchi *et alii* 1995). The subaerial part of the volcano was probably built up between 400-200 ka and 13 ka (Santo *et alii* 1995, Tranne *et alii* 2002, De Rosa *et alii* 2003), forming several monogenic and polygenic centers by explosive and effusive activity (Manetti *et alii* 1995, Santo 2000). There is no general consensus, however, on the age of the oldest rocks. A $^{39}Ar/^{40}Ar$ age of 1.0 ± 0.1 Ma has been measured in the lowermost outcropping rocks of Zucco Grande formation (Santo *et alii* 1995), whereas a K-Ar age of 219 ± 5 ka is considered by De Rosa *et alii* (2003) to date the oldest activity. Furthermore, on the basis of stratigraphic considerations, Tranne *et alii* (2002) suggested Filo del Banco formation as the oldest rocks, emplaced before the eustatic highstand episodes of pre-Tyrrhenian age (at ca. 400 ka). The Filicudi rocks mainly belong to the calc-alkaline and high-K calc-alkaline series, with compositions from basalts and high-K andesites to low-silica high-K dacites (Fig. 2). Few high-K basalts are also present ('La Canna' rocks). Basalts and basaltic andesites are characterized by low MgO (<6 wt%), Ni (<30 ppm), and Cr contents, associated with high Al_2O_3 contents (18-21 wt%; Francalanci *et alii* 2004a). The $^{87}Sr/^{86}Sr$ values (0.70402-0.70474) are overall higher in the mafic than in the sialic rocks (Francalanci and Santo 1993). Nd isotopes range from 0.51267 to 0.51276 and are negatively correlated with $^{87}Sr/^{86}Sr$ (Fig. 3). Pb isotopes cluster around $^{206}Pb/^{204}Pb$ = 19.31-19.67, $^{207}Pb/^{204}Pb$ = 15.64-15.69, and $^{208}Pb/^{204}Pb$ = 39.11-39.47 (Fig. 4 - Santo *et alii* 2004).

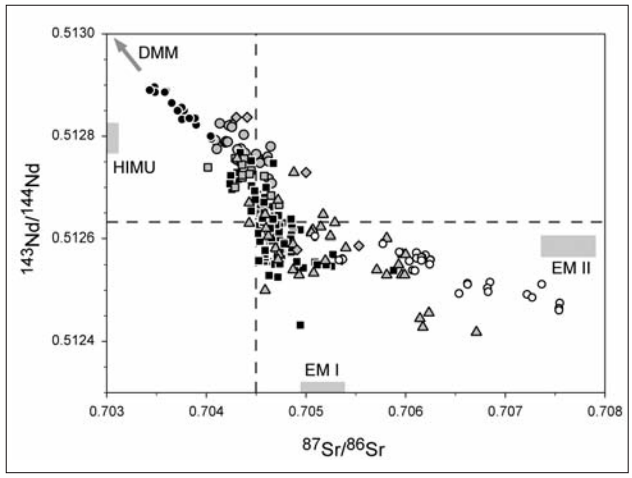

Fig. 3. $^{143}Nd/^{144}Nd$ *vs* $^{87}Sr/^{86}Sr$ diagram for Aeolian volcanic arc rocks. The fields of the different mantle components (DMM, HIMU, EM I, EM II) are from Zindler and Hart (1986) and Stracke *et alii* (2005). Data source and symbols as in Figure 2.

Salina is the second largest island of the Aeolian arc (26.8 km²), and is formed by two steep stratovolcanoes: Fossa delle Felci, 962 m a.s.l., and Monte dei Porri, 860 m a.s.l. The former represents the highest peak of the Aeolian Islands. The stratovolcanoes were built up between 168 and 13 ka and consist of a sequence of lava flows, domes, Strombolian scoriae, and pyroclastic deposits. The oldest subaerial rocks are basalts to basaltic andesites, followed by the eruption of few basalts to dacites and high-K calc-alkaline dacites; the youngest products vary from basalts to rhyolites (Fig. 2 - Keller 1980a, Calanchi *et alii* 1993, Ventura 1995, De Rosa *et alii*

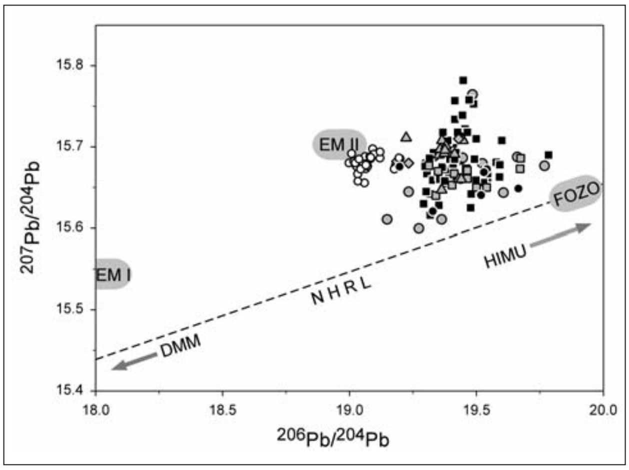

Fig. 4. $^{207}Pb/^{204}Pb$ *vs* $^{206}Pb/^{204}Pb$ diagram for Aeolian volcanic arc rocks. The fields of the different mantle components (DMM, HIMU, FOZO, EM I, EM II) are from Zindler and Hart 1986 and Stracke *et alii* (2005); NHRL: Northerm Hemisphere Reference Line. Data source and symbols as in Figure 2.

2003). Sr isotopes range from 0.70410 to 0.70463 and show a well-defined negative correlation with Nd isotopes (Fig. 3). Pb isotopes have a relatively large variation in $^{206}Pb/^{204}Pb$ (19.15-19.77), fairly constant $^{207}Pb/^{204}Pb$ (15.60-15.76), and minor variations in $^{208}Pb/^{204}Pb$ (38.97-39.51) (Fig. 4). Whole-rock $\delta^{18}O$ values range from +6.4‰ to +8.5‰ and are positively correlated with Sr isotopes (Ellam *et alii* 1989, Ellam and Harmon 1990, Francalanci *et alii* 1993b, Gertisser and Keller 2000).

Lipari is the largest island (38 km²), rising from a depth of ~1000 m below sea level to an elevation of 602 m a.s.l. The subaerial activity took place from 223 ka to 580 AD, and an intense submarine fumarolic activity is still present along the western and eastern coasts of the island. The island is composed of several pyroclastic cones and dome structures (Crisci *et alii* 1991, De Rosa *et alii* 2003). Lipari rocks are mainly calcalkaline basaltic andesites and high-K calc-alkaline andesites and rhyolites. Few latites and high-K calc-alkaline dacites are also present (Fig. 2). Sr isotopes are quite high and variable (0.7042-0.7067) and negatively correlated with Nd isotopes (0.5128-0.5124; Fig. 3). Pb isotopes do not display significant variations ($^{206}Pb/^{204}Pb$ = 19.22-19.45, $^{207}Pb/^{204}Pb$ = 15.65-15.71, $^{208}Pb/^{204}Pb$ = 39.26-39.43) (Fig. 4) (Bargossi *et alii* 1989, Crisci *et alii* 1991, Esperança *et alii* 1992, Gioncada *et alii* 2003).

Vulcano is the southernmost island, with an area of 22 km² and a maximum elevation of 500 m a.s.l. (Fig. 1). It is characterized by two volcano-tectonic subcircular depressions: the oldest Piano caldera in the SE and the youngest Fossa caldera in the N-W. The earliest rocks of the primordial Vulcano are high-K calc-alkaline and shoshonitic basalts and shoshonites with a maximum age of 136 ka. The Fossa active composite tuff cone, 391 m high, developed in the middle of the Fossa caldera, during the last 6 ky, with the youngest eruption in 1888-1890. Hydromagmatic and pyroclastic fall deposits, and lava flows built up the Fossa cone. Since 1890, Vulcano is only characterized by an intense fumarolic activity of high temperature (up to ~650 °C). Vulcanello, the Northern peninsula of Vulcano, consists of a tabular lava platform and three mainly pyroclastic cones. It appeared as a new islet in 183 BC, and recent eruptions occurred in the sixth and sixteenth centuries, followed by intense fumarolic activity until 1878. Around 1550 AD, Vulcanello islet was connected with Vulcano Island by sand accumulation forming the isthmus area between the two islands. The last erupted products of Vulcanello have a trachytic composition, whereas all the other rocks are leucite-bearing shoshonites and latites (Keller 1980b, Frazzetta *et alii* 1984, De Astis *et alii* 1997). Basalts and basaltic andesites form a single cluster straddling the boundary line between high-K calc-alkaline and shoshonitic fields, and are considered to form a single shoshonitic series (Fig. 2). Samples with higher K_2O contents (*e.g.*, K_2O > 3.5 wt% at SiO_2 < 56 wt%) form the leucite-bearing K-series (Fig. 2). Shoshonitic rocks with SiO_2 < 56 wt% represent the oldest rocks (>30 ka), whereas the most silicic shoshonitic rocks and potassic rocks are the youngest products (<30 ka) (De Astis *et alii* 2000). The $^{87}Sr/^{86}Sr$ values range from 0.70417 to 0.70587 and increase with decreasing MgO and $^{143}Nd/^{144}Nd$ values (0.51240-0.51277) (Figs. 3, 5). The $^{206}Pb/^{204}Pb$ values display significant variations (19.28-19.76), along with $^{207}Pb/^{204}Pb$ (15.66-15.82; Fig. 4) and $^{208}Pb/^{204}Pb$ (39.0-39.5). Whole-rock $\delta^{18}O$ values range from +6.2‰ to +8.1‰ and are positively correlated with Sr isotopes (Ellam and Harmon 1990; De Astis *et alii* 1997, 2000; Del Moro *et alii* 1998; Gioncada *et alii* 2003; Zanon *et alii* 2003).

Panarea is the smallest island (~3.3 km²) (Fig. 1), formed by the emerged part (421 m a.s.l.) of a cone-shaped edifice, rising from ~1500 m b.s.l. Eastward, other emerged rocks of this edifice form the small Islets of Lisca Bianca, Lisca Nera, Bottaro, Panarelli, Dattilo, and Basiluzzo. The subaerial activity of Panarea developed between 149 and 54 ka. An intense fumarolic activity has recently been discovered between the Islets of Bottaro and Dattilo and at Calcara on Panarea Island (Gabbianelli *et alii* 1990, Calanchi *et alii* 2002, Lucchi *et alii* 2003). Panarea rocks are mainly high-K calc-alkaline andesites and dacites, with minor calc-alkaline and high-K calc-alkaline basaltic andesites and rare rhyolites. Some shoshonitic rocks have been also found as xenoliths in Lisca Bianca and submarine rocks (Fig. 2). Sr isotopes range from 0.70404 to 0.70573 and are negatively correlated with Nd isotopes (0.51256-0.51284) (Fig. 3). Pb isotopes are around $^{206}Pb/^{204}Pb$ = 19.18-19.43, $^{207}Pb/^{204}Pb$ = 15.68-15.71 (Fig. 4), and $^{208}Pb/^{204}Pb$ = 39.13-39.36. $^{87}Sr/^{86}Sr$ values increase from calc-alkaline to high-K calc-alkaline mafic rocks, whereas the opposite is exhibited by $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ values (Calanchi *et alii* 2002).

Stromboli, the northernmost island, has an area of ~12 km², an elevation of 924 m a.s.l., and rises from ~2000 m b.s.l. Seven main phases of activity have been recognized along the geologic history of the subaerial Stromboli Volcano. Several volcano collapses alternated with volcano building periods. Sector and flank collapses during the last 13 ky have led to the formation of the peculiar feature of Sciara del Fuoco scar, a steep trough on the NW flank of the volcano (Hornig-Kjarsgaard *et alii* 1993, Pasquarè *et alii* 1993, Tibaldi 2001). Stromboli has the largest compositional variation of the Aeolian volcanic arc, ranging from calc-alkaline to potassic series (Fig. 2). The Strombolicchio neck, with a calc-alkaline basaltic andesitic composition, represents the remnants of an older volcano (~200 ka), located to the NE, which had a structure directly connected with the submarine cone of Stromboli (Gabbianelli *et alii* 1993). The main Stromboli island was formed in the last 100 ky (Gillot and Keller 1993). Recent Strombolian activity has taken place for the past ~2000 yr from different vents, sited in a crater terrace at 750 m as.l. It consists of continuous degassing and periodic discrete explosions erupting small amounts of scoria bombs and lapilli, ashes, and blocks. The normal activity is periodically broken by eruptive crises, which include either lava flows or much more violent explosions, rarely injuring the villages. The latest crises, occurred in the periods between December 2002-July 2003 and February-March 2007, and were characterized by a continuous lava flow eruption and a paroxysm, with also a tsunami episode in the former crisis. Incompatible trace element contents increase from calc-alkaline to potassic series, whereas MgO, CaO, and compatible trace element contents decrease. Sr isotopes are quite variable (0.70507-0.70757) and increase from calc-alkaline to potassic rocks, whereas Nd isotopes decrease (0.51245-0.51261) (Fig. 3). Pb isotopes cluster around $^{206}Pb/^{204}Pb$ = 19.00-19.20, $^{207}Pb/^{204}Pb$ = 15.66-15.70 (Fig. 4), and $^{208}Pb/^{204}Pb$ = 39.04-39.17 (Francalanci *et alii* 1988, 1989, 1999, 2004b; Luais 1989; De Astis *et alii* 2000; Tommasini *et alii* 2007). Whole-rock $\delta^{18}O$ values range from +6.1‰ to +7.9‰ and are negatively correlated with Sr isotopes (Ellam and Harmon 1990).

The juvenile products of all Aeolian Islands volcanoes are typically porphyritic with a porphyritic index between 15 and 40 vol%, decreasing toward rhyolites, which are sometimes aphyric. Olivine phenocrysts are abundant in basalts and decrease toward basaltic andesites and andesites, in which they are usually resorbed. In shoshonitic and potassic rocks, olivine is stable up to shoshonites and latites and, at Vulcano, it also persists as resorbed grains in some rhyolitic rocks. Plagioclase is the dominant phenocryst phase, and it is ubiquitous together with clinopyroxenes (diopside and augite). Pigeonite is found as microphenocrysts and in the groundmass at Salina and Lipari. Orthopyroxene is common in andesites and dacites (calc-alkaline and high-K calc-alkaline series), even though few microphenocrysts are present in basalts and basaltic andesites. Orthopyroxene is lacking at Vulcano and in the shoshonitic and potassic rocks of Stromboli, except for its occurrence as microphenocrysts in latites. Hornblende is sporadically found in basaltic andesites, and its amount increases in andesites, dacites, and rhyolites. It does not occur at Vulcano and is rare at Stromboli (only in high-K calc-alkaline andesites). Biotite is present in high-K calc-alkaline andesites of Filicudi and Stromboli, in dacites and rhyolites of Salina, in latites of Stromboli, and in trachytes of Vulcano, whereas it is an accessory phase at Panarea. Sanidine is present in the groundmass of all the Vulcano rocks. As phenocryst, it only occurs in the trachytes of Fossa and Vulcanello and in the rhyolites of Lentia and Lipari. Leucite appears in the groundmass and as microphenocryst in the potassic rocks. Ti-magnetite, ilmenite, and apatite are found as accessory minerals. Mineral phases, in particular plagioclase and clinopyroxene, usually show complex zoning (Romano 1973; Keller 1980a, 1980b; Francalanci *et alii* 1989, 1993a; Crisci *et alii* 1991; Francalanci and Santo 1993; Peccerillo *et alii* 1993; Ventura 1995; De Astis *et alii* 1997; Calanchi *et alii* 2002; Gioncada *et alii* 2003).

4. Discussion

The Aeolian volcanic arc rocks have compositions ranging from basalts to rhyolites and belong to the five magmatic series typical of orogenic settings. The age of subaerial volcanism does not have a systematic correlation with the geographical position. The oldest subaerial rocks of the Aeolian volcanoes are found at Filicudi (probably ~400 ka), Strombolicchio (~200 ka), and Lipari (~223 ka). They are sequentially followed by Salina (~168 ka), Panarea (~149 ka), Vulcano (~136 ka), and Alicudi and Stromboli (<100 ka). Overall, in a time span of ~250 ky, all the volcanoes emerged from the sea without any spatial trend. The cessation of the volcanic activity began in the western part of the arc, because no eruptions or fumarolic manifestations have been recorded in recent times at Alicudi and Filicudi (the age of the youngest rocks is ~28 and ~13 ka, respectively). The last eruptions at Lipari took place in 580 AD, an intense fumarolic activity is present at Panarea, whereas Vulcano and Stromboli are still active. The cessation of the volcanic activity to the west of the Tindari-Letojanni-Malta transcurrent fault (Fig. 1) is probably linked to the absence of active deep seismicity in that sector of the arc (Falsaperla *et alii* 1999).

Only a few correlations are present between the age and the compositional characteristics of the rocks. For example, the most acidic rocks of the arc were erupted during the youngest activity at Salina, Lipari, Panarea, and Vulcano, in the central part of the archipelago. An increase of silica content with time has been also observed at Alicudi. At Stromboli, on the contrary, the youngest rocks have a more mafic composition. A general increase of potassium content with time is present at Vulcano, Stromboli, Lipari, and Panarea (Basiluzzo) (from calc-alkaline to shoshonitic and potassic series), although magmas with lower potassium content have been erupted in recent times at Panarea (calcalkaline), Stromboli (shoshonitic), and Vulcano (shoshonitic). Furthermore, potassium contents do not show any correlation with the depth of the subducted slab.

In contrast to the poor age-related compositional trends, most of the geochemical and isotopic variations

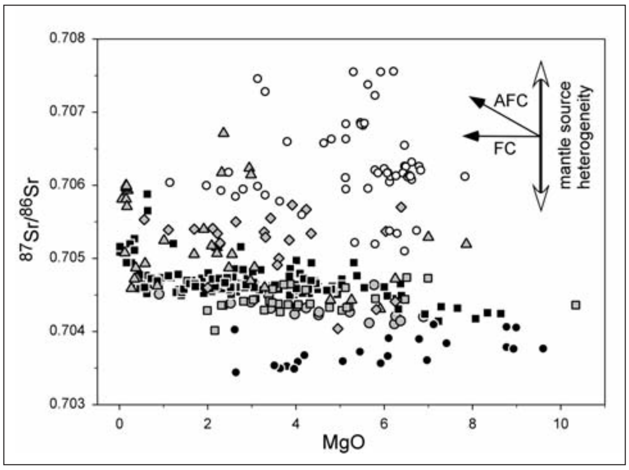

FIG. 5. $^{87}Sr/^{86}Sr$ *vs* MgO diagram diagram for Aeolian volcanic arc rocks. Arrows indicate the effects of mantle source heterogeneity and low pressure differentiation processes (Fractional Crystallization, and Assimilation and Fractional Crystallization) on rock composition. Data source and symbols as in Figure 2.

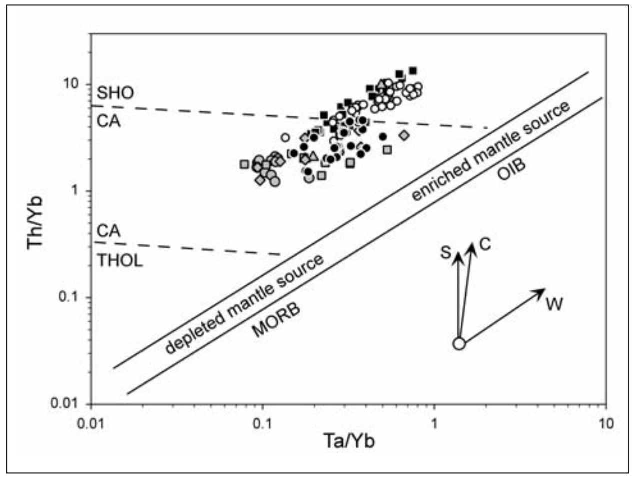

FIG. 6. Th/Yb *vs* Ta/Yb diagram for the mafic rocks (MgO > 4 wt%) of the Aeolian volcanic arc, showing the difference between subduction-related and oceanic basalts derived from depleted sources (MORB) and enriched sources (OIB). Dashed lines separate the boundaries of the tholeiitic (THOL), calc-alkaline (CA) and shoshonitic (SHO) fields. Vectors shown indicate the influence of subduction components (S), within plate enrichment (W), and crustal contamination (C). Data source and symbols as in Figure 2.

do clearly delineate geographical trends, from west to east. A decoupling between the behaviour of isotopic ratios and trace element contents and ratios is observed, however, especially among mafic calc-alkaline rocks. Indeed, isotope ratios mostly change from the western to the eastern sector of the arc, whereas element contents and ratios vary from the central to the external parts of the archipelago (Francalanci *et alii* 1993b, 2004a).

The large compositional variability of the Aeolian volcanic arc is due to several magma differentiation processes, encompassing shallow-level magma evolution and mantle source heterogeneity.

4.1. *Magma Differentiation at shallow Levels*

Complex processes of magma evolution played important roles in determining the compositional variations occurring within each single volcano of the Aeolian volcanic arc (Francalanci *et alii* 2004a and reference therein). Fractional crystallization (FC) has been the main process for generating large compositional changes within each single magmatic series (FIG. 5). The Aeolian rhyolites, in particular, derived from less-evolved magmas by crystal fractionation processes, rather than crustal anatexis (*e.g.*, Calanchi *et alii* 1993, 2002; De Astis *et alii* 1997, 2000; Del Moro *et alii* 1998; Gioncada *et alii* 2003; Francalanci *et alii* 2004a).

Crustal assimilation has been often coupled with fractional crystallization (AFC process). This process was found to have affected the evolution of most of the intermediate and acidic Aeolian volcanic arc magmas (FIG. 5). The presence of cordierite-, garnet-, sillimanite-, and andalusite-bearing andesitic and dacitic lavas at Lipari, the widespread occurrence in most of the Aeolian island rocks of restitic quartzite nodules, and partially melted crustal xenoliths are a clear evidence for the occurrence of crustal contamination. AFC played a minor role at Alicudi and Stromboli, but was more important at Lipari, Vulcano, and Salina (Crisci *et alii* 1991; Esperança *et alii* 1992; Francalanci and Santo 1993; De Astis *et alii* 1997, 2000; Gertisser and Keller 2000; Calanchi *et alii* 2002; Gioncada *et alii* 2003; Vaggelli *et alii* 2003; Zanon *et alii* 2003; Santo *et alii* 2004). Crustal assimilation also occurred as AEC (assimilation + equilibrium crystallization), in which hotter and more mafic magmas, *en route* to the surface, were able to assimilate the continental crust to a greater extent than evolved magmas (*e.g.*, Huppert and Spark 1985). This mechanism has been invoked for the evolution of Alicudi, Stromboli potassic rocks, Filicudi, and some Panarea magmas (Francalanci *et alii* 1988, 1989; Peccerillo and Wu 1992; Francalanci and Santo 1993; Peccerillo *et alii* 1993, 2004).

Mixing between different magmas has been another recurrent process of evolution in the Aeolian volcanoes. This process has been documented as repeated input of fresh magma in a continuously replenished + tapped + crystallizing ± assimilating magma chamber (RTF ± A) (Francalanci *et alii* 1989, 1993a; Calanchi *et alii* 1993; De Astis *et alii* 1997, 2000). Mixing plus crystallization has been the main process of evolution in the magmas feeding the present-day activity of Stromboli, and these processes allow the magma chamber to maintain a steady-state condition during the continuous volcanic activity (Francalanci *et alii* 1999). RTFA-like processes have been proposed for the evolution of magmas at Stromboli and Vulcano (Francalanci *et alii* 1989, 1993a and references therein; De Astis *et alii* 2000). It is also noteworthy that potassic rocks have quite an evolved character (FIGS. 2, 5). At Vulcano, the mafic shoshonitic rocks display an increase in Sr isotopes (FIG. 5) and decrease in Nd and Pb isotope ratios with increasing degree of evolution, suggesting the occurrence of AFC

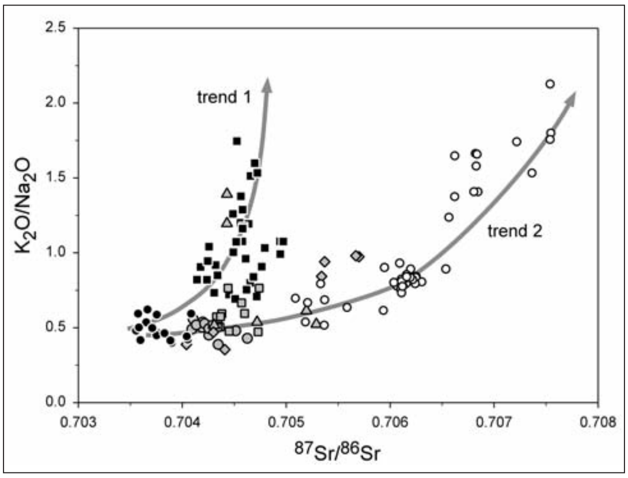

FIG. 7. K_2O/Na_2O *vs* $^{87}Sr/^{86}Sr$ diagram for the mafic rocks ($MgO > 4$ wt%) of the Aeolian volcanic arc, highlighting two trends of systematic enrichment of K_2O and radiogenic Sr. Starting from the Alicudi, Salina and Panarea calc-alkaline basalts, the first trend is delineated by the shoshonitic and potassic series of Vulcano and Lipari, whilst the second trend is mainly delineated by the calc-alkaline, shoshonitic and potassic series of Stromboli.

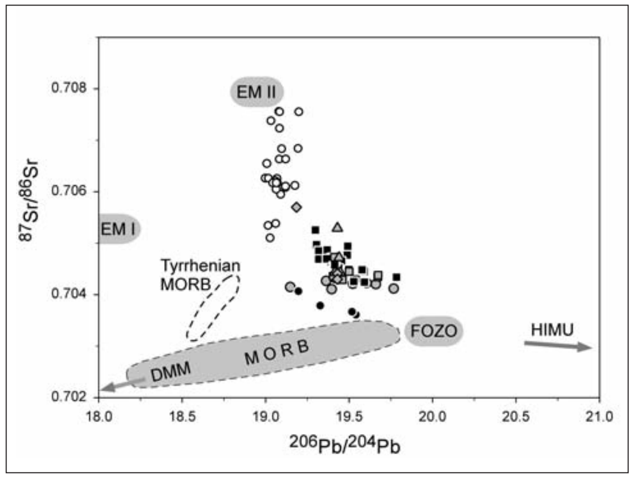

FIG. 8. $^{87}Sr/^{86}Sr$ *vs* $^{206}Pb/^{204}Pb$ diagram for the mafic rocks ($MgO > 4$ wt%) of the Aeolian volcanic arc, defining a trend between an EM II and a high-μ (high $^{238}U/^{204}Pb$, FOZO, HIMU) mantle component. The fields of the different mantle components (DMM, HIMU, EM I, EM II) are from Zindler and Hart (1986) and Stracke *et alii* 2005, whilst the field of Tyrrhenian MORB is from Beccaluva *et alii* (1990) and Gasperini *et alii* (2002). Data source and symbols as in Figure 2.

processes (De Astis *et alii* 1997, 2000). The fact that Vulcano potassic rocks plot at the more-evolved extreme of the evolutionary trend described by the selected shoshonitic rocks suggests that potassic magmas could also have derived from mafic shoshonitic melts by RTFA-like processes.

Polybaric magma evolution within each single volcano has been proposed by several authors on the basis of geochemical and mineralogical data (*e.g.*, Stromboli: Francalanci *et alii* 1989; Salina: Calanchi *et alii* 1993; Filicudi: Francalanci and Santo 1993; Vulcano: De Astis *et alii* 1997). Crystallization at higher depth for Filicudi and Salina magmas with respect to the other calc-alkaline magmas has been inferred from the different Al_2O_3, MgO, Sr, and compatible trace element contents of calc-alkaline magmas (Francalanci 1994, Francalanci *et alii* 2004a). Studies on fluid inclusions found in restitic quartzite nodules and from crystal chemistry of clinopyroxene confirm a polybaric rest in most of the volcanoes, giving a total pressure range of 0.6-0.1 GPa (Vaggelli *et alii* 2003, Nazzareni *et alii* 2001, Frezzotti *et alii* 2003, Zanon *et alii* 2003 and references therein). In particular, on the basis of crystal-chemical variations in clinopyroxene, Nazzareni *et alii* (2001) suggested that Filicudi, the oldest products of Salina, and, to a lesser extent, Alicudi magmas crystallized at higher pressure, in the lower crust or at the mantle-crust boundary. However, fluid inclusions data on quartzite nodules at Alicudi, Filicudi, Salina, and Vulcano have given opposite pressure results, with higher pressure for Alicudi and Vulcano and lower pressure for Salina and Filicudi (Frezzotti *et alii* 2003, Zanon *et alii* 2003). On the other hand, Filicudi and the oldest products of Salina display other common characteristics that could favour crystallization at high pressure, such as, for example, the absence of caldera collapses during their volcanological history (Nazzareni *et alii* 2001), which, in contrast, occurred in the central and western islands.

4.2. *Compositional Heterogeneity of the Mantle Source*

The above mentioned evolutionary processes have had a major role during parental magma differentiation and were liable to modify both trace element and isotopic ratios in the most evolved products (FIG. 5). In order to minimize compositional differences due to low-pressure evolutionary processes and to unravel mantle source heterogeneity, we have selected the most mafic rocks ($MgO > 4$ wt%) outcropping in each island.

The mafic rocks of the Aeolian volcanic arc have a clear subduction-related signature (FIG. 6) demonstrating the involvement of oceanic crust (basalt and sediment) fluids as metasomatic agents of the mantle wedge above the subducting Ionian lithosphere. The mafic rocks have also an increase in the potassium content positively correlated with their incompatible trace element content and radiogenic isotope signature. For example, K_2O/Na_2O and $^{87}Sr/^{86}Sr$ increase systematically from calc-alkaline, shoshonitic and potassic series (FIG. 7), providing evidence for a continuous enrichment of lithophile elements in the mantle source. The Alicudi, Salina and Panarea calc-alkaline basalts define the unradiogenic end from which two distinct trends develop: the first is delineated by the shoshonitic and potassic series of Vulcano and Lipari; the second is mainly delineated by the calc-alkaline, shoshonitic and potassic series of Stromboli.

The radiogenic isotope signature of the Aeolian volcanic arc rocks define a trend between an EM II-like and a high-μ (high $^{238}U/^{204}Pb$) mantle component (FIG. 8). In all radiogenic isotope diagrams, with no exception, the rocks of Alicudi and Salina are the closest to the

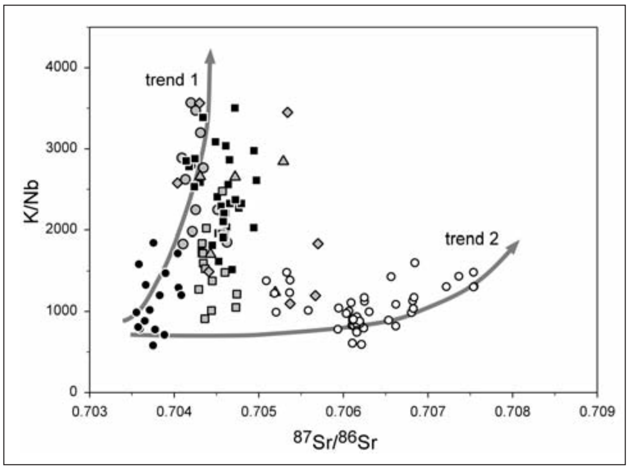

FIG. 9. K/Nb *vs* $^{87}Sr/^{86}Sr$ diagram for the mafic rocks (MgO > 4 wt%) of the Aeolian volcanic arc, defining two distinct trends developing from the calc-alkaline basalts of Alicudi and branching towards the calc-alkaline series of Salina and the shoshonitic series of Vulcano (trend 1), and the potassic series of Stromboli (trend 2). Data source and symbols as in Figure 2.

high- μ mantle end-member, whereas the rocks of Stromboli trend toward the EM II end-member. The Sr, Nd, and Pb isotope signature, along with key trace element ratios of the Alicudi and Salina basalts (*e.g.*, Ta/Yb *vs* Th/Yb; FIG. 6) suggest that the high-μ mantle component differs from the classical HIMU or FOZO mantle components defined on the basis of ocean island basalt (OIB) geochemistry (Zindler and Hart 1986, Stracke *et alii* 2005). On the other hand, the Tyrrhenian Sea basalts define a trend between the EM II component and a mid-ocean ridge basalt (MORB)-like component (FIG. 8), consistent with new asthenospheric mantle impinging at the base of the lithosphere and interacting with it. In plots of large ion lithophile elements (LILE)/Nb *vs* $^{87}Sr/^{86}Sr$ (*e.g.*, K/Nb *vs* $^{87}Sr/^{86}Sr$; FIG. 9), the data define two distinct trends developing from the calc-alkaline basalts of Alicudi and branching towards the shoshonitic series of Vulcano and the potassic series of Stromboli. U and Th concentrations in all the magma series are remarkably high, ranging from 1 to 8 ppm and from 2 to 27 ppm, respectively. U/Th *vs* Th (FIG. 10) demonstrate that the metasomatic agent responsible for mantle wedge metasomatism is dominated by melts released by the downgoing Ionian slab although in some volcano, such as Stromboli, the calc-alkaline mafic magmas exhibit a significant ^{238}U excess, implying the contribution of aqueous fluids from the downgoing slab as well (Tommasini *et alii* 2007), which is not readily apparent on trace element ratio diagrams (FIG. 10).

4.3. *The potential Magma Sources*

The Aeolian volcanic arc represents the product of subduction of the Ionian plate beneath Calabria (*e.g.*, Faccenna *et alii* 2003, Mattei *et alii* 2004). On the basis of geophysical studies (Panza 1985; Bassi *et alii* 1997; Di Stefano *et alii* 1999; Gvirtzman and Nur 1999, 2001; Meletti *et alii* 2000; Wortel and Spakman 2000; Faccenna *et alii* 2001, 2007; Panza *et alii* 2003; Scrocca *et alii* 2003; Pontevivo and Panza 2006; Montuori *et alii* 2007), the deep structure underneath the Aeolian volcanic arc consists of Calabrian continental crust to a depth of some 20 km, a thin lithospheric mantle lid to a depth of ~40 km, a convective asthenospheric mantle wedge to a depth of some 200 km, and then the subducting Ionian slab.

4.3.1. The mantle Wedge

The trace element composition of the convective mantle wedge below the Aeolian volcanic arc prior to the recent subduction enrichment process can be estimated using the composition of the magmas generated as a consequence of asthenospheric upwelling in the central Tyrrhenian Sea. As the available data for Tyrrhenian Sea basalts are from dredged samples (Beccaluva *et alii* 1990) (*i.e.*, likely to have suffered some hydrothermal and sea-floor alteration) we have made our selection with a bias towards the least enriched compositions and we have also corrected their $^{87}Sr/^{86}Sr$ on the basis of their $^{143}Nd/^{144}Nd$ using the mantle array (DePaolo and Wasserburg 1979) as a reference. In our inverse modelling we have assumed that the composition of the transitional MORB of the Tyrrhenian Sea (Beccaluva *et alii* 1990, Gasperini *et alii* 2002) has been generated by 10% batch melting of the asthenospheric mantle, using the bulk partition coefficients of Workman and Hart (2005). The estimated geochemical composition of the mantle wedge mimics that of enriched MORB-source mantle (E-DMM; Workman and Hart 2005), and although speculative, it is not critical to the model proposed below, as its low trace element budget is overwhelmed by the trace element and isotopic signal of the subducting components during the recent enrichment processes.

4.3.2. The subducted Slab

The geodynamic setting of the Aeolian Islands differs from that of most subduction-related volcanoes in the high-angle (70°) geometry of the Benioff Zone and a very low geothermal gradient (Carminati *et alii* 2005, Pasquale *et alii* 2005). This results in the occurrence of dehydration reactions at greater depths than in other arcs (Davies and Stevenson 1992, Peacock *et alii* 1994). Consequently, this characteristic must be taken into account in considering the fate of the oceanic crust in the subduction factory. The subducted Ionian oceanic slab consists of sediment, basalt and oceanic lithospheric mantle. In terms of the trace element budget delivered to the overlying mantle wedge, the contribution of the oceanic lithospheric mantle, commonly regarded as being a refractory harzburgite, is considered negligible, excluding any H_2O released during the dehydration of serpentine, chlorite and other high-pressure H_2O-bearing phases (*e.g.*, Stalder *et alii* 2001, Iwamori 2004, Rüpke *et alii* 2004). These minerals, upon reaching their stability limits, dehydrate and release supercritical fluids, which flush the oceanic crust and transfer fluid-mobile elements to the overlying mantle wedge, lowering the solidus of the peridotite and triggering melting.

On the other hand, the two major components of the oceanic crust (altered basalt, including the intrusive counterpart, and sediment cover) play a fundamental role in recycling lithophile elements back into the mantle wedge through the prograde dehydration reactions occurring during slab subduction (*e.g.*, Hawkesworth *et alii* 1991, 1997; Peacock *et alii* 1994; Elliott *et alii* 1997; Turner *et alii* 1997; Plank and Langmuir 1998). The geochemical characteristics of altered oceanic basalt (AOB) mostly reflect hydrothermal alteration at mid-ocean ridges, which continues more slowly as the sea-floor ages (*e.g.* Staudigel *et alii* 1995, Becker *et alii* 2000). The most significant modifications are the enrichments in K, Ba, Rb, Cs, U, and radiogenic Sr (Staudigel *et alii* 1995). In terms of Pb isotopes, U enrichment during mid-ocean ridge hydrothermal alteration of the basaltic component results in an increase in $^{238}U/^{204}Pb$ (μ), and consequently in a time-integrated increase of $^{206}Pb/^{204}Pb$. Assuming an original $^{206}Pb/^{204}Pb$ of 18.65, intermediate between DMM and E-DMM (Workman and Hart 2005), and a μ of 35 (*e.g.*, Staudigel *et alii* 1995), developed during sea-floor alteration, the basaltic component could reach a $^{206}Pb/^{204}Pb$ of 19.47-19.75 in 150-200 Myr, a time span consistent with the age of the Western Tethyan ocean basins (Catalano *et alii* 2001, Bortolotti and Principi 2005, Finetti 2005, Stampfli 2005).

The subducted pelagic sediments of the Ionian plate are the other major component capable of recycling lithophile elements back into the mantle. The relevant data are the sediment samples collected from Ocean Drilling Program (ODP) leg 160, Site 964; unfortunately, these are limited to Sr and Nd isotope data only (Weldeab *et alii* 2002), and hence we have to make some assumptions about the trace element budget of the sediment pile. A potential proxy for the subducted sediments could be the sediments cropping out in the Apennine chain. They constitute the terrigenous load accumulating in the Tethyan ocean basins, of which the Ionian plate represents one of the last remnants. Unfortunately, there is no comprehensive geochemical database on the Apennine sediments and this limits their use as a proxy of the subducted sediment. A global survey of sediments recycled into the mantle has been undertaken by Plank and Langmuir (1998) encompassing the main arc-trench systems around the world; this resulted in an average composition of globally subducted sediments (GLOSS). It is tempting to use GLOSS as a proxy of the subducting sediments of the Ionian plate. The available data on sediments cropping out in the Apennine chain reveal, however, systematic low Ba/Th < 60 (*e.g.*, Di Battistini *et alii* 2001, Di Leo *et alii* 2002, Melluso *et alii* 2003, Avanzinelli *et alii* 2008), whereas GLOSS has a Ba/Th = 110. In contrast, the average composition of Post Archean Shales (Taylor and McLennan 1985) has Ba/Th < 60, whereas the other trace elements are not greatly different from GLOSS. We therefore used the Post Archean Shale composition as a proxy of the subducting sediment pile.

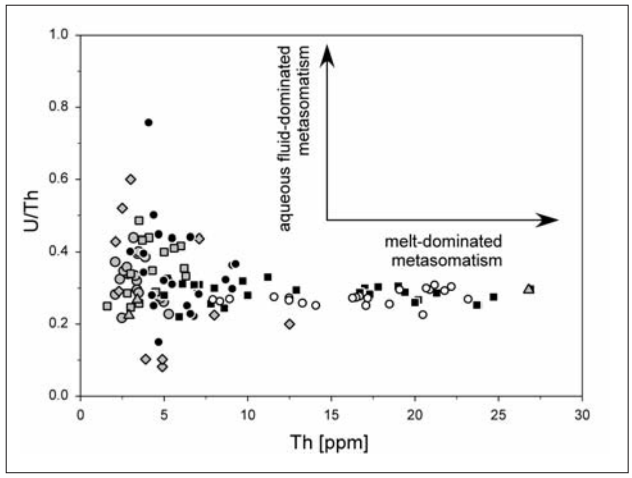

FIG. 10. Plot of U/Th *vs* Th for the mafic rocks (MgO > 4 wt%) of the Aeolian volcanic arc, demonstrating metasomatism of the mantle wedge dominated by melts from the subducting Ionian slab and not aqueous fluids, as indicated by the displacement in magma composition expected from the two vectors reported in the diagram. Data source and symbols as in Figure 2.

4.3.3. The Calabrian Lithosphere

The trace element budget of the continental crust exceeds greatly that of the continental lithospheric mantle (*e.g.*, Taylor and McLennan 1985, McDonough 1990). Consequently, the 20 km thick crust forming the basement below the Aeolian volcanic arc has a greater potential than the 20 km thick lithospheric mantle lid to modify the composition of the mantle-derived magmas *en route* to the surface, as a consequence of low-pressure assimilation-fractional crystallization processes. On the other hand, the frozen outer portion of the magma chamber and feeding dykes can serve as chemical insulators, preventing significant assimilation of the wall-rocks. The occurrence of open-system processes can be established using a number of key trace element ratios and radiogenic isotopes because systematic variations are to be expected. For example, the increase of Ba/K with $^{87}Sr/^{86}Sr$ is a robust tool to discriminate between crustal assimilation and source enrichment (Turner *et alii* 1996). Available data for the Calabrian basement confirm that the geochemical characteristics of the mafic magmas of the Aeolian volcanic arc are dominantly controlled by source enrichment processes (FIG. 11) with negligible crust involvement.

4.4. *The mantle Wedge Enrichment*

In this section we assess the enrichment processes responsible for the geochemical signature of the mantle source of the Aeolian volcanic arc magmas and the role played by subducted components. The Aeolian mafic magmas have among the highest Th contents of volcanic arc magmas (FIG. 10), including those from the Philippines and Indonesia (*e.g.*, McDermott *et alii* 1993; Vroon *et alii* 1993, 1996; Turner and Foden 2001). This suggests, along with the low U/Th of the samples and

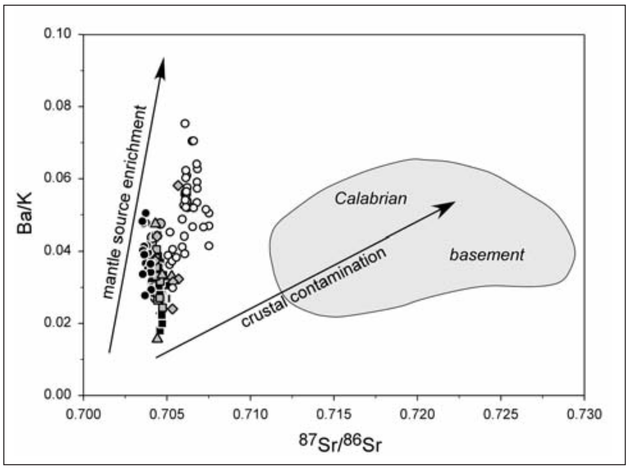

FIG. 11. Plot of Ba/K *vs* $^{87}Sr/^{86}Sr$ for the mafic rocks (MgO > 4 wt%) of the Aeolian volcanic arc along with the field of the Calabria basement rocks (Del Moro *et alii* 2000, Fornelli *et alii* 2002). The two vectors indicate the expected magma enrichment caused by crustal contamination by the Calabria basement as opposed to mantle source processes (*e.g.*, Turner *et alii* 1996).

the radiogenic isotope characteristics (FIGS. 3, 8), that their geochemistry is dominated by a sedimentary component in the mantle source rather than slab fluids (*e.g.*, Hawkesworth *et alii* 1997).

A key factor that helps to understand the unique characteristics of the magmas of Aeolian volcanic arc is the geometry of the Benioff Zone, which dips at a high angle (70°), associated with a very low geothermal gradient. A number of studies have suggested that the transfer of sedimentary components from the subducted slab into the mantle wedge occurs as a partial melt rather than by bulk addition (*e.g.*, Hawkesworth *et alii* 1997, Turner *et alii* 1997, Sigmarsson *et alii* 1998, Johnson and Plank 1999), despite the fact that most thermal models of subduction zones predict temperatures at the slab-wedge interface that are too low for sediment melting (*e.g.*, Peacock *et alii* 1994, Rüpke *et alii* 2004). In the case of the Aeolian volcanic arc, this dichotomy can possibly be resolved because of the high-angle dip of the Ionian plate, which causes dehydration and 'melting' reactions to occur at greater depths (equivalent to >4GPa) than in many volcanic arcs (*e.g.*, Davies and Stevenson 1992). The increase of the dehydration and 'melting' pressure for a given lithology results in the convergence of the composition of the low-density aqueous fluid (low-temperature side) and the dense hydrous silicate melt (high-temperature side) along a miscibility gap, which eventually disappears; the intersection of the fluid-saturated solidus with the closure of the fluid-melt solvus at high pressure is termed the second critical end-point of the solidus (Boettcher and Wyllie 1969). Beyond this pressure, the discontinuous solidus reaction involving the aqueous fluid (low T) and the hydrous silicate melt (high T) is replaced by a continuous reaction involving a supercritical liquid (Kessel *et alii* 2005), which spans a chemical continuum between the composition of the aqueous fluids and hydrous silicate melts at lower pressure. In particular, the low-pressure difference between the partition coefficients of fluid-mobile (*e.g.*, Rb, Ba, Pb, U) and fluid-immobile (*e.g.*, Th, REE) trace elements ceases to exist in supercritical liquids, and all the lithophile trace elements have melt-like solubilities (Kessel *et alii* 2005).

In basaltic and pelitic systems, the second critical end-point of the solidus is at ~5-6 GPa (Schmidt *et alii* 2004, Kessel *et alii* 2005). Melting of the slab at P > 5 GPa generates supercritical liquids whose potassium content should be positively correlated with pressure as demonstrated by the experiments of Johnson and Plank (1999), albeit limited to 2 and 4 GPa. In the case of the Aeolian volcanic arc, the positive correlation between K_2O/Na_2O and $^{87}Sr/^{86}Sr$ (FIG. 7) provides evidence of mantle metasomatism by supercritical liquids enriched in K and radiogenic Sr.

As the subducted slab includes basalt and sediment, their distinct trace element leverage on the composition of the mantle wedge can possibly generate a different geochemical signal in the erupted magmas (*e.g.*, Class *et alii* 2000, Hochstaedter *et alii* 2001). In the case of the Aeolian volcanic arc, the two distinct trends in the K_2O/Na_2O and K/Nb *vs* $^{87}Sr/^{86}Sr$ diagram (FIGS. 7, 9) requires two geochemically distinct enriching agents both having high K_2O/Na_2O and K/Nb (and also other LILE/Nb): one with a relatively unradiogenic Sr isotope composition ($^{87}Sr/^{86}Sr < 0.705$), possibly originating from the basaltic component, and the other with a more radiogenic Sr isotope composition ($^{87}Sr/^{86}Sr >$ 0.705), possibly related to the subducted sediment component.

Following the modelling developed by Tommasini *et alii* (2007), the mantle source of the Aeolian volcanic arc magmas can be reproduced by metasomatism of the mantle wedge with different mixtures of the two supercritical liquids originating from the subducted slab at ~6 GPa and 900 °C, and a partial melting degree of some 4% and 20% for the basaltic and sedimentary component, respectively. The two supercritical liquids, unlike aqueous fluids originating at shallower depths (< 120 km), have melt-like solubilities for LILE and high field strength elements (HFSE) (Kessel *et alii* 2005). This means that high LILE/HFSE values can be obtained not only for ratios involving fluid-mobile elements (*e.g.*, K/Nb, U/Nb) but also for ratios of fluid-immobile elements such as Th/Nb, depending on the amount of rutile remaining in the residue. The basaltic component of the slab will deliver a supercritical liquid with relatively unradiogenic $^{87}Sr/^{86}Sr$ and high LILE/Nb, whereas the sedimentary component will also yield a supercritical liquid with high LILE/Nb albeit more radiogenic $^{87}Sr/^{86}Sr$. This determines, along with the mixing proportions of the two supercritical liquids with the mantle wedge, the development of the two distinct trends in LILE/Nb *vs* $^{87}Sr/^{86}Sr$ diagrams (*e.g.*, FIG. 9). The mantle source of the Alicudi, Panarea and Vulcano magmas (trend 1; FIG. 9) requires a metasomatizing agent consisting mainly of the basalt-derived supercritical liquid, whereas the mantle source of the potassic series of Stromboli (trend 2; Fig. 9) requires a supercritical liquid mainly formed by the sediment-derived supercritical liquid. The other mafic magmas of the Aeolian volcanic arc fall in between these two extreme trends and require intermediate mixtures of the two supercritical liquids.

Another important geochemical characteristic is that the more the relative proportion of the supercritical liquid from the basaltic component, the higher the $^{206}Pb/^{204}Pb$ (Fig. 8) owing to the high-μ developed during mid-ocean ridge hydrothermal alteration. Consequently, the involvement of two distinct supercritical liquids enriching the mantle wedge can account for the trend between the EM II and high-μ mantle components delineated by the Aeolian volcanic arc magmas (Fig. 8).

We can thus envisage a scenario where these high-P supercritical liquids migrate through the overlying mantle wedge at a very fast rate owing to their low viscosity, and form a metasomatized mantle that subsequently, upon melting, originates the different types of magma series building up the different volcanoes of the Aeolian Islands.

4.5. *Geodynamic Model of the Subduction Factory of the Aeolian volcanic Arc*

A realistic geodynamic model of the Aeolian volcanic arc subduction factory must take into account both the key geochemical characteristics of the erupted magmas and the structure of the Aeolian arc subduction zone. The predominant geochemical characteristics of the mantle source of the Aeolian volcanic arc magmas have been imparted by the different mixtures of the two supercritical liquids released by the basaltic and sedimentary component. Despite this general agreement, however, there are a number of discrepancies in terms of U-Th systematics and aqueous fluid-mobile trace elements that require another mantle enrichment stage occurred at shallower depths (~4 GPa, 800 °C) and induced by aqueous fluids, along with a delay of some 350 kyr between the two stages to allow the decay of the ^{230}Th excess of the enriched mantle source after the first metasomatic event and explaining the ^{238}U excess present in some magmas of Stromboli (Tommasini *et alii* 2007). Fitting these geochemical constraints into a geodynamic model is not straightforward, although some constraints can be made based on the model proposed for the Mariana arc lavas by Elliott *et alii* (1997), adapting it to the structure of the Aeolian arc subduction zone.

The simplest model must be based upon the low geothermal gradient of the Aeolian arc subduction zone, which dips at a high angle (70°), leading to melting of the subducting slab at depths >150 km with the formation of supercritical liquids. The supercritical liquids from the basalt and sediment components of the slab rise into the overlying mantle wedge and react to hybridize it. During the delay between the two stages, the enriched mantle wedge is dragged downward with the subducting slab, and the ^{230}Th excess created by the addition of the supercritical liquids decays. In the second stage, dehydration reactions in the subducted oceanic crust and the underlying harzburgite occurs at depths shallower than 150 km, releasing aqueous fluids into the overlying enriched mantle wedge and creating the ^{238}U excess as measured in some of the Stromboli magmas (Tommasini *et alii* 2007). The aqueous fluid enrichment is critical to lower the solidus of the mantle wedge and trigger melting. A higher proportion of slab-derived aqueous fluids in the islands from the central sector of the arc, which also promotes a higher degree of mantle partial melting, has been also proposed on the basis of the decoupling between trace-element and Sr isotope variations in the Aeolian calc-alkaline and high-K calc-alkaline rocks (Francalanci *et alii* 1993b, 2004a, 2007).

The critical parameter in this geodynamic model is the delay between the two stages. If we take at face values the nominal pressures (4 and 6 GPa) and temperatures (800 and 900 °C) adopted by Tommasini *et alii* (2007), the geothermal gradient should vary from ~5 °C/km (Stage I) to ~6.6 °C/km (Stage II). The causes of these P-T variations of the descending slab in 350 kyr, could be due to variations of the shear heating parameter (*e.g.*, Davies and Stevenson 1992, Roselle *et alii* 2002) in response to slab roll-back (*e.g.*, Gvirtzman and Nur 1999, 2001; Faccenna *et alii* 2001) and the likely slowing down of the convergence rate of the almost exhausted Ionian slab. Whatever the reason and the actual P-T-t path of the Ionian slab, the important point outlined by the geochemical characteristics of the Aeolian volcanic arc magmas is the occurrence of two mantle enrichment stages (supercritical liquids and aqueous fluids) that are separated by a time interval of some 350 kyr and retain their discrete chemical characteristics until they are brought together in the mantle source, shortly before melting.

5. Concluding Remarks

We have presented a comprehensive trace element and radiogenic isotope review of the Aeolian volcanic arc magmas, one of the most intriguing volcanic arc on Earth. The variety of magma compositions erupted requires a complex model of mantle source enrichment.

The magmas of Aeolian volcanic arc originated from a mantle source that experienced two distinct enrichment processes by different parts of the subducting oceanic crust of the Ionian slab. The first was caused by supercritical liquids originating from the basaltic and sedimentary component of the subducting slab at ~6 GPa and 900 °C. The second was caused by aqueous fluids, originating again from the basaltic and sedimentary components of the slab, released from another part of the subducted Ionian slab located at shallower depth (~4 GPa) and 800 °C. The high-angle dip of the Ionian slab determined the superimposition of the metasomatizing agents of the two enrichment processes in the same volume of mantle wedge, explaining the occurrence of such different magma series in a relatively restricted area (Fig. 1).

As a corollary, the geochemical and isotopic signature of the mantle source of the Aeolian volcanic arc magmas places important constraints on the isotopic polarity from Southern Latium to the Aeolian arc (*e.g.*, Hawkesworth and Vollmer 1979, Ellam *et alii* 1989, Conticelli *et alii* 2002), attributed to an increasing within-plate (HIMU) component. The trend towards high $^{206}Pb/^{204}Pb$ of the putative 'HIMU' mantle component delineated by the Alicudi, Panarea and Vulcano magmas (FIG. 8) can be equally formed during metasomatism of the pre-existing mantle wedge by the supercritical liquid and subsequently aqueous fluid released by the subducted altered basalt of the Ionian plate. Similarly, the trend towards high K/Nb (and also high LILE/Nb; Francalanci *et alii* 1993, 2007; Peccerillo *et alii* 1993, 2004) and relatively low $^{87}Sr/^{86}Sr$ of the Alicudi, Panarea and Vulcano basalts (FIG. 9) can be explained by the predominance of the enriching agents (supercritical liquid and aqueous fluid) from subducted altered basalt in their mantle source.

The involvement of the subducted basalt of the Ionian slab in forming the high $^{206}Pb/^{204}Pb$ mantle component is in keeping with the orogenic trace element characteristics of the Alicudi, Panarea and Vulcano magmas (Francalanci *et alii* 1993, 2007; Peccerillo *et alii* 1993, 2004), and requires neither lateral inflow of foreland mantle material (*e.g.*, Peccerillo 2001, Trua *et alii* 2002) nor a hot mantle plume in the centre of the Tyrrhenian basin (*e.g.*, Gasperini *et alii* 2002; Bell *et alii* 2004). The former is a very sluggish process, and the latter is contrary to the radiogenic isotope signature of the Tyrrhenian Sea basalts.

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